Chapter 6
Ice Forces on Structures

6-1. Introduction

Basically, three approaches may be taken to determining ice forces on structures:

- Analytical, using the mechanical properties of ice and theory of applied mechanics.

- Experimental, using measurements from full-scale structures or scale models.

- Empirical, using the experience of successful and unsuccessful structures.

There are at present many difficulties with a strictly analytical approach, and current practice tends to depend more on empirical procedures, modified to some degree by experimental and analytical results. The concept of a design ice pressure—normally regarded as total ice force, divided by projected area of contact, normal to the direction of ice action—is firmly entrenched in engineering practice and is generally useful, being analogous to concepts of wind pressure or soil pressure. It must be emphasized, however, that ice pressure is not the same as ice strength, and that the relationship between pressure and strength depends on the geometrical relationship and other details of ice–structure interaction. The ice strength should be defined in relation to a particular test procedure and should be regarded as a material property.

6-2. Main Types of Ice–Structure Interaction

Most cases of ice action on structures fall into one of the four following categories. This chapter covers the first two types of forces only. Research on the second two types is still being conducted and the reader should contact appropriate research organizations.

a. Dynamic ice forces. These forces come from floating ice sheets and floes driven by streamflow, currents, or wind. This is normally the critical mode of action for structures in rivers and may be so in some lake situations. If the structure face subject to ice impact is vertical, the ice normally fails by crushing and splitting, and the forces that develop are horizontal. If the structure face is sufficiently inclined, the ice fails by bending and shear, and both horizontal and vertical force components are developed.

b. Static ice forces. These forces come from a more or less intact ice sheet subject to thermal expansion and contraction, or subject to steady pressure from wind or currents. Normally, the ice does not fail, but deforms plastically around the structure.

c. Ice forces from a mass of broken pack or "rubble" ice driven against a structure. This happens in a river ice jam or along lake shores. The ice pack acts somewhat like a granular soil. Pile-up on shore and forces on ice booms, bridges, and other structures fall into this category.

d. Uplift and drawdown forces. These forces are associated with adhesion of floating ice to piles, etc. Forces are generated when static water pressures change because of tides, reservoir operation, lake level changes, etc.

6-3. Dynamic Forces—General

Most ice sheets are large enough so that impact forces are limited by ice failure in the weakest mode permitted by the mechanics of the interaction as the structure penetrates the ice—crushing, splitting, shear, or bending. For smaller sheets or wide structures, the maximum force may be limited by the kinetic energy available at the moment of impact and complete penetration may not occur.

a. *Vertical surfaces.* With vertical piles, pier noses, etc., failure usually takes place by crushing at the surface of contact (Figure 6-1). Spalling may occur on top and bottom ice surfaces, and thin sheets may buckle. A neat slot is often left as the ice moves past. (If the ice sheet is large enough, current drag can maintain a steady speed.) Smaller sheets may crush briefly and then stop, rotate and move downstream, or they may split longitudinally.

b. Inclined surfaces. The mode of ice failure for inclined faces is variable and complex (Figure 6-2). At angles of greater than 75 degrees between the pier nose and the horizontal, crushing failure is most likely. At intermediate angles of inclination, some ice may crush, while other ice "rides up" and breaks in a three-dimensional pattern. If the inclination angle is less than 60 degrees, failure is nearly always by shear–bending. Factors such as friction, pier-width-to-ice-thickness ratio, and cracks in the sheet affect the preference for crushing or bending failure. Horizontal forces from bending failure are far less than forces from crushing failure; therefore, inclined faces are desirable. However, other considerations (economics, catching of driftwood, etc.) have led to a decline in the popularity of severely inclined faces for river piers.

c. Conical structures. Conical towers are favored for coastal and ocean structures (e.g., lighthouses), since ice fails by bending into wedge-shaped slabs (Figure 6-3).

d. Force fluctuations. A more or less universal characteristic of dynamic ice forces is the presence of rapid force fluctuations, which may be periodic or random, or both. Their significance depends on the dynamic response characteristics of the structure. No special allowance for forced vibrations has normally been made in pier design. In the case of sloping structures, a lower-frequency periodic fluctuation results from a ride-up and break sequence.

6-4. Vertical Piers or Piles

Currently, all bridges are designed using AASHTO specifications. A standard of 2.76 MPa (400 psi) is used as the crushing strength of the ice, and the design load is obtained by multiplying this times the ice thickness and times the pier width

$$\frac{P}{bh} = 2.76 \text{ MPa } (400 \text{ psi}). \tag{6-1}$$

Analysis and experiments indicate the existence of something like the following basic relationship

$$\frac{P}{bh} = C_i \cdot m \cdot \sigma_c \cdot k \tag{6-2}$$

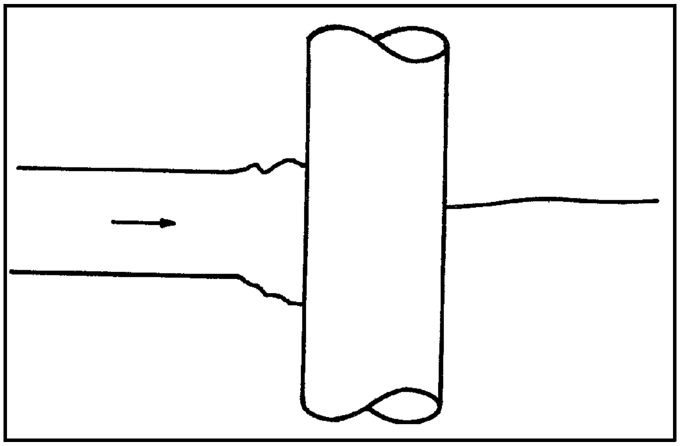

Figure 6-1. Ice failing against a vertical surface

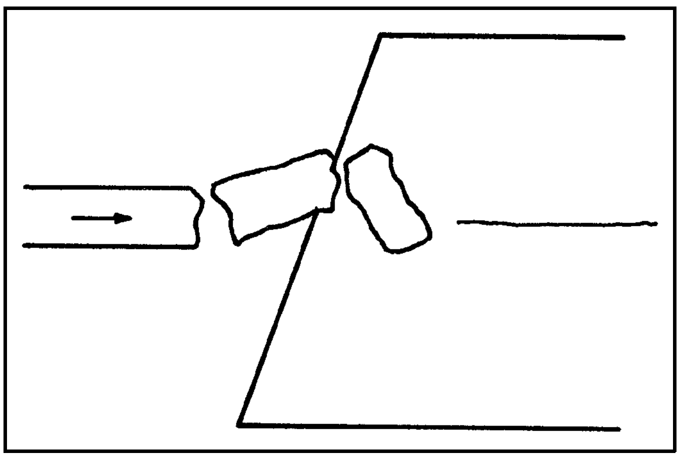

Figure 6-2. Ice failing against an inclined surface

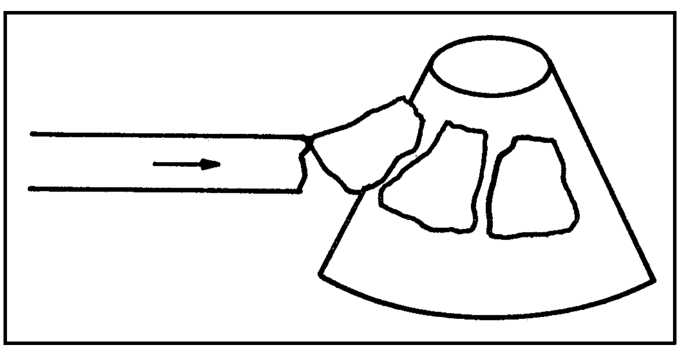

Figure 6-3. Ice failing against a conical surface

where

P = horizontal force developed

C_i = "indentation" coefficient

m = plan shape coefficient

σ_c = compressive strength of ice

b = width or diameter of pile or pier normal to ice movement

h = ice thickness

k = "contact" coefficient.

The ice pressure P/bh is therefore equal to the ice crushing strength σ_c multiplied by three coefficients. The indentation coefficient C_i is found experimentally and analytically to be a function of b/h, as given by Figure 6-4. The shape coefficient m is not very sensitive to plan shape and is usually taken as 0.9 for semicircular noses. Korzhavin (1971) quoted the "contact" coefficient as in the range of 0.4 to 0.7. The combination $m \cdot k$ is therefore on the order of 0.5.

a. Effective ice strength. The current Canadian bridge design code provides for "effective ice strength" values ranging from 0.69 to 2.76 MPa (100 to 400 psi), and for modifying factors, dependent on b/h, that follow the curve shape of Figure 6-1 but imply an included $m \cdot k$ value of about 0.5. The background to these code values is difficult to explain in a few words since it has undergone successive modifications. However, the Canadian code does recommend an "effective ice strength" of

0.69 MPa (100 psi) when breakup occurs at melting temperatures and the ice moves in small pieces that are essentially disintegrated.

1.38 MPa (200 psi) when breakup occurs at melting temperatures but the ice moves in large pieces that are generally sound.

2.07 MPa (300 psi) when breakup consists of an initial movement of the entire ice sheet or when large sheets of sound ice strike piers.

2.76 MPa (400 psi) when breakup occurs with an ice temperature significantly below the melting point and the ice movement consists of large sheets.

The AASHTO 1978 interim specifications have essentially adopted the Canadian code.

b. Other considerations. If values of ice compressive strength are determined for a specific situation, insertion into Equation 6-2 of values of C_i taken from Figure 6-4 will probably give reasonable values of P when $m \cdot k$ is taken as about 0.5. Note that because of the dependence of C_i on b/h, ice force does not reduce in proportion to pier width, especially at low values of b/h. In the limit, a knife-edge pier will still experience substantial forces.

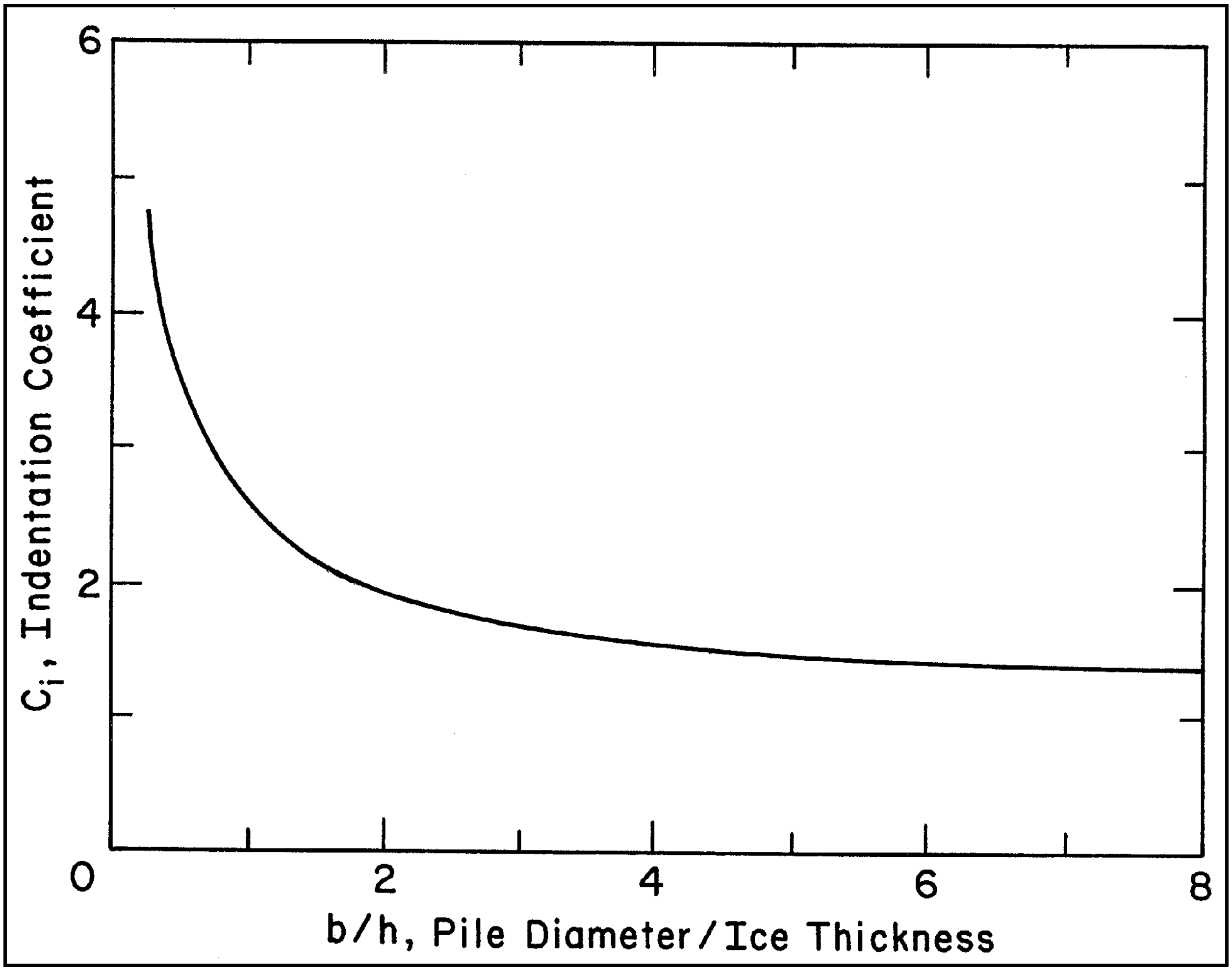

Figure 6-4. Indentation coefficient versus *b/h*

6-5. Dynamic Forces—Inclined Piers

The problem of calculating the forces on inclined piers has been attacked analytically many times since the 19th century, with considerably varying results, depending upon the assumptions made. Because of these variable results, the approach has usually been to consider static forces rather than dynamic forces that vary with time. Some formulas make the force proportional to bh, and others to h^2. Experimental evidence is insufficient to settle the question, but intuition suggests that the truth lies somewhere between these extremes. On the basis of dimensional analysis, it appears to be immaterial which is used, because the ratio of force to bh or to h^2 should depend in part on the aspect ratio b/h, as in the vertical case.

a. Reduction coefficient. The current Canadian code takes a conservative approach to inclined piers by providing reduction coefficients to the basic formula of Equation 6-2. If the angle of the pier nose to the horizontal is less than 75 degrees, a reduction factor of 0.75 is used, and if the angle is less than 60 degrees, 0.50 is used.

b. Example. Consider an ice sheet 3 feet (0.9 meters) thick failing against a 5-foot-wide (1.5-meter-wide) pier that slopes 65 degrees with respect to the horizontal. Assume the compressive strength of the ice to be 400 psi (2.76 MPa). Equation 6-1 gives

P = (0.75) (400 psi) (36 in.) (60 in.) = 648,000 lb.

In SI units

P = (0.75) (2.76 MPa) (0.9 m) (1.5 m) = 2.79 MN.

6-6. Dynamic Forces—Conical Towers

In the case of conical towers, the ice failure pattern is complex and the force on the pier apparently depends substantially on the resistance of the broken ice to displacement, as well as on breaking forces. Generally speaking, the horizontal force depends primarily on the ice thickness, the strength in bending, and the cone angle, but also on the waterline diameter and the coefficient of friction between ice and cone. For steep angles, results are sensitive to assumed friction and the crushing mode of failure may occur. Since very few conical structures have been built, the state of the art is constantly changing and consultation with a research organization such as CRREL is recommended for particular problems.

6-7. Transverse Forces on Piers

The 1978 Canadian code provides that the transverse force shall be not less than 15 percent of calculated axial force, or the appropriate component based on angle of approach, if known. This provision implies penetration of the ice by the pier nose and is not intended to provide for sideways impact on a vertical face, which might produce very large forces.

6-8. Static Force—Thermal Expansion

Equations are available that predict the temperature of ice based on an energy balance between the atmosphere and the ice. The atmospheric parameters needed are air temperature, air vapor pressure, wind, and cloud cover. The thermal expansion of unrestrained ice behaves as most normal materials do. The thermal strain is equal to a thermal expansion coefficient times the change in temperature. If the ice is restrained or partially restrained, the stress–strain law for ice must be used to predict the thermal stress. This law is nonlinear with stress and is time-dependent. For example, if the ice temperature changes slowly, the induced thermal stress will have time to relax owing to creep of the ice. Hence, the rate of temperature change is an important factor in predicting thermal stresses. The effect of a snow cover is to slow down the rate of temperature change. Even a thin snow cover can reduce thermal stresses drastically. Recent practice in Canada is to design for 146–219 kN/m (10,000–15,000 lb/ft) for dams and other rigid structures. For flexible structures, such as sluice gates, 73 kN/m (5000 lb/ft) is used. Values measured by the Bureau of Reclamation on reservoirs are from 51 to 292 kN/m (3500 to 20,000 lb/ft). The higher value is for a reservoir with steep, rocky banks. Closely spaced spillway piers at a dam are designed with an increased effective pier width. The effective pier width is equal to the actual pier plus one-third of the pier spacing distance.

6-9. References

a. Required publications.
None.

b. Related publications.

Korzhavin 1971
Korzhavin, K.N. 1971. *Action of Ice on Engineering Structures*, Draft Translation, TL 260, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.